

ROUTING AND ACTION

MEMORANDUM

ROUTING

TO:(1) Electronics Division (Qiu, Joe)

Report is available for review

(2) Proposal Files Report No.: -II

Proposal Number: 66414-EL-II.3

DESCRIPTION OF MATERIAL

CONTRACT OR GRANT NUMBER: W911NF-14-1-0572

INSTITUTION: Purdue University

PRINCIPAL INVESTIGATOR: Peide Ye

TYPE REPORT: Final Report

DATE RECEIVED: 11/19/15 4:59PM

PERIOD COVERED: 9/1/14 12:00AM through 5/31/15 12:00AM

TITLE: Final Report: Ballistic Phosphorene Transistor

ACTION TAKEN BY DIVISION

(x) Report has been reviewed for technical sufficiency and IS ☒ IS NOT ☐ satisfactory.

(x) Material has been given an OPSEC review and it has been determined to be non sensitive and, except for manuscripts and progress reports, suitable for public release.

(x) Performance of the research effort was accomplished in a satisfactory manner and all other technical requirements have been fulfilled.

(x) Based upon my knowledge of the research project, I agree with the patent information disclosed.

Approved by SSL\JOE.QIU on 2/1/16 11:15AM

ARO FORM 36-E

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
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			5c. PROGRAM ELEMENT NUMBER 611102		
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13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT This is the final report for ARO Grant No. W911NF-14-1-0572 entitled "Ballistic Phosphorene Transistor" as a STIP award for the period 09/1/2014 through 5/31/2015. The ARO program director responsible for the grant is Dr. Joe Qiu. The PI is Prof. Peide Ye of Purdue University. The objective of this project is to explore phosphorene, a name we coined for a 2D atomic layer of black phosphorus (BP), which, unlike graphene, can have an inherent and direct bandgap on the order of 1 eV and, unlike MoS2 or other transition-metal dichalcogenides (TMDs) with strong d orbital coupling, can have carrier mobility on the order of 104 cm2/Vs. Thus, phosphorene can potentially					
15. SUBJECT TERMS Black Phosphorus, Phosphorene, FET					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Peide Ye
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 765-494-7611

Report Title

Final Report: Ballistic Phosphorene Transistor

ABSTRACT

This is the final report for ARO Grant No. W911NF-14-1-0572 entitled “Ballistic Phosphorene Transistor” as a STIP award for the period 09/1/2014 through 5/31/2015. The ARO program director responsible for the grant is Dr. Joe Qiu. The PI is Prof. Peide Ye of Purdue University. The objective of this project is to explore phosphorene, a name we coined for a 2D atomic layer of black phosphorus (BP), which, unlike graphene, can have an inherent and direct bandgap on the order of 1 eV and, unlike MoS2 or other transition-metal dichalcogenides (TMDs) with strong d-orbital coupling, can have carrier mobility on the order of 104 cm²/Vs. Thus, phosphorene can potentially overcome the challenges of all other 2D materials for ultra-scaled thin-body low-power transistor applications thereby transforming the electronics industry. Even more, phosphorene and few-layer phosphorene has very unique anisotropic transport properties which we have also first explored in transport. [1,2] In FY15, Professor Ye’s team investigated unique transport property and explore its potential applications in field-effect transistor at ballistic limit down to 15 nm channel region. His team studied the channel length scaling of ultra-thin phosphorene field-effect transistors (FETs), and discuss a scheme for using various contact metals to change transistor characteristics. Through studying transistor behaviors with various channel lengths, the contact resistance can be extracted from the transfer length method (TLM). With different contact metals, we find out that the metal/BP interface has different Schottky barrier, leading to a significant difference in contact resistance, which is quite different from previous studies of transition metal dichalcogenides (TMDs) such as MoS2 where Fermi-level is strongly pinned near conduction band edge at metal/MoS2 interface. The nature of BP transistors are Schottky barrier FETs, where the on and off states are controlled by tuning the Schottky barriers at the two contacts. His team also observed the ambipolar characteristics of BP transistors with enhanced n-type drain current and demonstrate that the p-type carriers can be easily shifted to n-type or vice versus by controlling the gate bias and drain bias as illustrated in Figure 1, showing the potential to realize BP CMOS logic circuits.[2] Due to the dominant contact resistance, the drain current of BP FETs doesn’t increase dramatically even with channel length down to 15nm. His team is working toward to develop an effective doping scheme on BP and phosphorene to significantly reduce the contact resistance and realize low-resistive ohmic contact ballistic transistors on BP and phosphorene.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received

Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received

Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

11/19/2015 1.00 Yexin Deng, Nathan J. Conrad, Zhe Luo, Han Liu, Xianfan Xu, Peide D. Ye. Towards High-Performance Two-Dimensional Black Phosphorus Optoelectronic Devices: the Role of Metal Contacts, IEDM[object Object] (12 2014)

11/19/2015 2.00 Han Liu, Yuchen Du, Yexin Deng and Peide D. Ye. Semiconducting black phosphorus: synthesis, transport properties and electronic applications, Chemical Society Review (07 2014)

TOTAL: 2

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Yexin Deng	1.00	
FTE Equivalent:	1.00	
Total Number:	1	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Peide Ye	0.05	
FTE Equivalent:	0.05	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Adam Charnas	1.00	
FTE Equivalent:	1.00	
Total Number:	1	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Total Number:

Names of personnel receiving PHDs

<u>NAME</u>
Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This is the final report for ARO Grant No. W911NF-14-1-0572 entitled “Ballistic Phosphorene Transistor” as a STIP award for the period 09/1/2014 through 5/31/2015. The ARO program director responsible for the grant is Dr. Joe Qiu. The PI is Prof. Peide Ye of Purdue University. The objective of this project is to explore phosphorene, a name we coined for a 2D atomic layer of black phosphorus (BP), which, unlike graphene, can have an inherent and direct bandgap on the order of 1 eV and, unlike MoS2 or other transition-metal dichalcogenides (TMDs) with strong d-orbital coupling, can have carrier mobility on the order of 104 cm²/Vs. Thus, phosphorene can potentially overcome the challenges of all other 2D materials for ultra-scaled thin-body low-power transistor applications thereby transforming the electronics industry. Even more, phosphorene and few-layer phosphorene has very unique anisotropic transport properties which we have also first explored in transport. [1,2] In FY15, Professor Ye’s team investigated unique transport property and explore its potential applications in field-effect transistor at ballistic limit down to 15 nm channel region. His team studied the channel length scaling of ultra-thin phosphorene field-effect transistors (FETs), and discuss a scheme for using various contact metals to change transistor characteristics. Through studying transistor behaviors with various channel lengths, the contact resistance can be extracted from the transfer length method (TLM). With different contact metals, we find out that the metal/BP interface has different Schottky barrier, leading to a significant difference in contact resistance, which is quite different from previous studies of transition metal dichalcogenides (TMDs) such as MoS2 where Fermi-level is strongly pinned near conduction band edge at metal/MoS2 interface. The nature of BP transistors are Schottky barrier FETs, where the on and off states are controlled by tuning the Schottky barriers at the two contacts. His team also observed the ambipolar characteristics of BP transistors with enhanced n-type drain current and demonstrate that the p-type carriers can be easily shifted to n-type or vice versus by controlling the gate bias and drain bias as illustrated in Figure 1, showing the potential to realize BP CMOS logic circuits.[2] Due to the dominant contact resistance, the drain current of BP FETs doesn’t increase dramatically even with channel length down to 15nm. His team is working toward to develop an effective doping scheme on BP and phosphorene to significantly reduce the contact resistance and realize low-resistive ohmic contact ballistic transistors on BP and phosphorene.

During this project, we have presented our research results in top 2D conferences and also published in top nanoelectronics journals as listed following.

Invited Conference Presentations:

1. Peide Ye, “Graphene and other 2D materials for high frequency devices,” IEEE MTT-S IMS2014 (International Microwave Symposium), Tampa Bay, USA, June 1-6, 2014.
2. Peide Ye, “Phosphorene as a new 2D material for nanoelectronic and optoelectronic applications,” 2014 Lester Eastman Conference on High Performance Devices, Cornell, August 5-7, 2014.
3. Peide Ye, ‘Device Perspective of 2D Materials Beyond Graphene,’ The 14th IEEE International Conference on Nanotechnology (IEEE Nano), Toronto, ON, Canada, August 18-21, 2014.
4. Peide Ye, ‘New Channel Materials and Devices Beyond Si CMOS,’ 2014 International Conference on Solid State Devices and Materials (SSDM 2014), Japan, Sept. 8-11, 2014. (Plenary Talk)
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6. Peide Ye, “ALD Applications for State-of-the-Art Nanoelectronics,” The 2nd International Conference on ALD Applications, China, October 16-17, 2014. (Keynote Talk)
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2. Yexin Deng, Nathan J. Conrad, Zhe Luo, Han Liu, Xianfan Xu, and Peide D. Ye, Towards High-Performance Two-Dimensional Black Phosphorus Optoelectronic Devices: the Role of Metal Contacts, 2014 International Electron Devices Meeting (IEDM 2014): December 15-17, 2014.
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2. Yexin Deng, Zhe Luo, Nathan J. Conrad, Han Liu, Yongji Gong, Sina Najmaei, Pulickel M. Ajayan, Jun Lou, Xianfan Xu and Peide D. Ye, Black Phosphorus-Monolayer MoS₂ van der Waals Heterojunction p-n Diode, ACS Nano Vol. 8, No. 8, 8292-8299, 2014.
3. Yuchen Du, Lingming Yang, Han Liu, and Peide D. Ye, Contact research strategy for emerging molybdenum disulfide and other two-dimensional field-effect transistors, APL Materials 2, 092510, 2104.
4. Yuchen Du, Han Liu, Yexin Deng, and Peide D. Ye, Device Perspective for Black Phosphorus Field-Effect Transistors: Contact Resistance, Ambipolar Behavior, and Scaling, ACS Nano Vol.8, No.10, 10035-10042, 2014.
5. Han Liu, Yuchen Du, Yexin Deng, and Peide D. Ye, Semiconducting Black Phosphorus: Synthesis, Transport Properties and Electronic Applications, Chemical Society Review 2015, 44, 2732, DOI:10.1039/c4cs00257a

Technology Transfer

Ballistic Phosphorene Transistor

Professor Peide D. Ye, Purdue University, STIP Award

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[1] H. Liu, A. T. Neal, Z. Zhu, D. Tomanek, and P. D. Ye, ACS Nano **8**, 4033-4041, 2014.

[2] Z. Luo, J. Massen, Y. Deng, Y. Du, R. Garrelts, M.S. Lundstrom, P.D. Ye, X. Xu, Nature Comm. 2015
DOI:10.1038/ncomms9572

[3] Y. Du, H. Liu, Y. Deng, and P.D. Ye, ACS Nano **8**, 10035-10042, 2014.

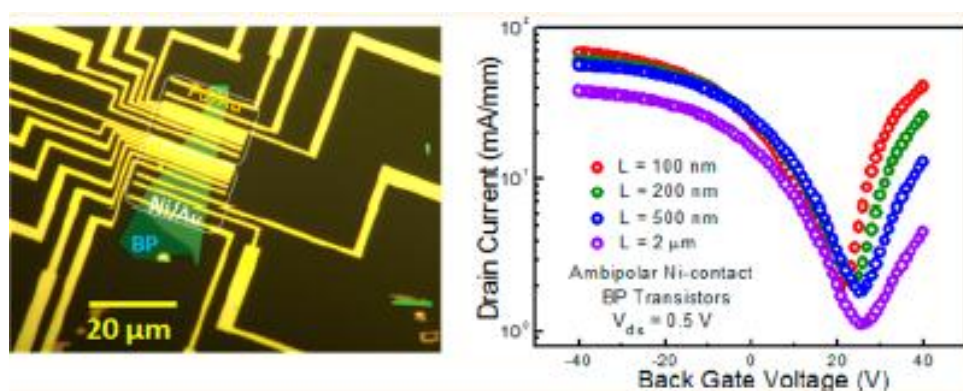


Figure 1: (left) Optical image of the ultra-thin BP FETs with Ni/Au and Pd/Au contacts on the same BP flake. (right) *I*-*V* transfer characteristic of Ni contact BP FETs with channel length from 2 μm to 100 nm.

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2. Yexin Deng, Zhe Luo, Nathan J. Conrad, Han Liu, Yongji Gong, Sina Najmaei, Pulickel M. Ajayan, Jun Lou, Xianfan Xu and Peide D. Ye, Black Phosphorus-Monolayer MoS₂ van der Waals Heterojunction p-n Diode, *ACS Nano* Vol. 8, No. 8, 8292-8299, 2014.
3. Yuchen Du, Lingming Yang, Han Liu, and Peide D. Ye, Contact research strategy for emerging molybdenum disulfide and other two-dimensional field-effect transistors, *APL Materials* 2, 092510, 2104.
4. Yuchen Du, Han Liu, Yexin Deng, and Peide D. Ye, Device Perspective for Black Phosphorus Field-Effect Transistors: Contact Resistance, Ambipolar Behavior, and Scaling, *ACS Nano* Vol.8, No.10, 10035-10042, 2014.
5. Han Liu, Yuchen Du, Yexin Deng, and Peide D. Ye, Semiconducting Black Phosphorus: Synthesis, Transport Properties and Electronic Applications, *Chemical Society Review* 2015, 44, 2732, DOI:10.1039/c4cs00257a